METROPOLITAN HIGHWAY SYSTEM
Stem to Stern Safety Review – Phase II

Volume II-1 – Phase II Overview and Summary

Commonwealth of Massachusetts

Final Report - Revised to Exclude Security Sensitive Information
August 15, 2008
WJE No. 2006.3651.2

Prepared for:
Commonwealth of Massachusetts
Executive Office of Transportation

Prepared by:
Wiss, Janney, Elstner Associates, Inc.
330 Pfingsten Road
Northbrook, Illinois 60062
847.272.7400 tel | 847.291.9599 fax

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Gary J. Klein
Project Manager
Licensed Structural Engineer
Illinois 4082
Temporary Permit Massachusetts 2006-119-PE

Robert Carasitti
Schirmer Engineering Corporation
Life Safety Team Leader
Licensed Professional Engineer
Massachusetts 39551

William J. Nugent
President
Licensed Professional Engineer
Massachusetts 45590

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STEM TO STERN SAFETY REVIEW MAP

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REVISED TO EXCLUDE SECURITY SENSITIVE INFORMATION

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WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

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INTRODUCTION

At the request of the Massachusetts Governor's Office and pursuant to Executive Order 474, Wiss, Janney, Elstner Associates, Inc. (WJE) performed a "stem to stern" safety review of the Central Artery/Tunnel (CA/T) project, as well as other elements of the Metropolitan Highway System (MHS). Life safety systems of the MHS were investigated by WJE's subconsultants, Schirmer Engineering Corporation and Environmental Systems Design, Inc. (ESD). Phase II of the stem to stern safety review, administered by the Executive Office of Transportation (EOT), began on 1 July 2007.

The Phase II report is comprised of twenty-four volumes, starting with this report, Volume II-1 – Phase II Overview and Summary. Volumes II-2 though II-11 describe follow-up investigation of the principal elements of the CA/T, as well as the Sumner and Callahan Tunnels.

Volume	Report Topic
II-2	Tunnels-Structural
II-3	Tunnels-Finishes
II-4	Sumner and Callahan Tunnels
II-5	Concrete Viaducts
II-6	Steel Viaducts
II-7	Zakim Bridge
II-8	Leverett Bridge
II-9	Buildings
II-10	Signs and Luminaires
II-11	Life Safety Systems

Volumes II-12 through II-18 report on special studies of selected elements and systems for which further investigation was recommended based on Phase I review findings. By definition, these "special studies" involve an in-depth look at issues that were considered to be important to safety, as listed below:

Volume	Report Topic
II-12	Incomplete Tendon Grouting
II-13	Concrete Overlays
II-14	Pattern Cracking
II-15	Fire Performance of Adhesive Anchors
II-16	Tunnel Leaks
II-17	Building Leaks
II-18	CA/T Ventilation Systems

Volumes II-19 through II- 24 report on the review of other elements of the MHS:

Volume	Report Topic
II-19	Sumner and Callahan Ventilation Buildings
II-20	Sumner and Callahan Life Safety Systems
II-21	CANA Life Safety Systems
II-22	Prudential Tunnel Life Safety Systems
II-23	Prudential Tunnel
II-24	Boston Extension

As a precursor to Phase II, some of the concerns identified in Phase I were studied under Phase IA, including certain high-priority safety issues as well as items for which the scope of Phase II investigation was not fully defined:

Volume	Report Topic
IA-1	I-93 Tunnel Leaks, Repairs, and Corrosion Mitigation
IA-2	Review of Anchorage Issues for CA/T Tunnel Finishes
IA-3	Investigation of Sumner Tunnel Liner
IA-4	Investigation of Field Patching of Concrete Viaducts
IA-5	Investigation of Post-Tensioning Duct Grouting
IA-6	Investigation of the Zakim Bridge Stay Cable Anchorages
IA-7	Review of Seismic Design Criteria

The following sections of this summary report describe the background of the stem to stern safety review and summarize the Phase IA and Phase II findings. The findings judged to be most significant are discussed herein; refer to the reports listed above for additional details and a complete listing of findings.

The reader is advised that this version of the summary report has been revived to exclude security sensitive information.

STRUCTURE DESCRIPTION AND SCOPE OF SAFETY REVIEW

The Metropolitan Highway System

The Central Artery/Tunnel (CA/T) comprises most of the Metropolitan Highway System (MHS). Elements of the MHS that are not part of the CA/T project include the Sumner Tunnel, the Callahan Tunnel, the Central Artery North Area (CANA) Tunnel, and the Boston Extension (I-90 west of I-93 to MA-128).

The following paragraphs describe the Central Artery/Tunnel system and other elements of the MHS.

Central Artery/Tunnel. Two principal elements comprise the CA/T: the *central artery*, a 4.3-mile reconstruction of Interstate 93 from Massachusetts Avenue through downtown Boston to Cambridge Street in Charlestown; and the *tunnel*, a 3.9-mile extension of Interstate 90 eastward from I-93, below the Fort Point Channel and Boston Harbor, to Logan Airport. (Refer to the map of the stem to stern safety review provided on page i.)

The mainstay of the CA/T project was replacement of the elevated central artery through downtown Boston with the Thomas P. "Tip" O'Neill, Jr., Tunnel. The O'Neill Tunnel was built using slurry wall and cut and cover construction for 1.6 miles beneath downtown Boston, while keeping the existing elevated artery open to traffic. The I-90 Connector tunnel, which crosses under the Fort Point Channel, was built using cut and cover methods and site-built immersed tube construction, as well as tunnel jacking below commuter rail lines. Immersed tubes, fabricated in Baltimore, were sunk beneath Boston Harbor to support the Ted Williams Tunnel. The CA/T project also incorporates two Charles River crossings: the Leonard P. Zakim Bunker Hill Bridge, an asymmetrical cable-stayed structure carrying I-93 across the Charles River; and the Leverett Bridge, a tapered steel box girder structure crossing the Charles River between the CANA loops and Leverett Circle.

In total, the CA/T project includes more than 161 lane miles of interstate highway and interchanges. As can be seen from the map at the front of this report, approximately half of these lane miles are in tunnel, one third are elevated, and the remainder are at grade or in *boat structures*, the transition structures between at-grade and tunnel sections. Most elevated sections of the CA/T employ either steel or concrete box girder construction.

Tunnel ventilation fans are housed in eight ventilation buildings, of which one is an air intake structure. The ventilation buildings are typically concrete-framed structures below grade and steel-framed structures above grade, located along the tunnels and near the tunnel portals. Thirteen medium-sized buildings house the Operations Control Center (OCC), emergency response centers, maintenance buildings, and electrical substations. In addition, there are more than thirty smaller buildings, mainly pump stations and tunnel egress stairs.

The CA/T project life safety systems consist of several detection, response, and protection systems and features, as follows:

- Fire Resistive Construction
- Fire Detection Systems
- Communication Systems
- Traffic Control Systems
- Fire Department Apparatus

- Standpipe Systems and Water Supplies
- Portable Fire Extinguishers
- Ventilation System
- Emergency Response Plans and Control of Hazardous Materials
- Emergency Egress Features
- Operations and Control Systems
- Power Systems

Construction of the CA/T started in 1991 and was completed in 2007. Significant CA/T project dates include the opening of the Ted Williams Tunnel in 1995, the opening of the Zakim Bridge in 2002, and the openings of the I-90 Connector Tunnel and the I-93 O'Neill Tunnel in 2003.

The CA/T project was initially managed by the Massachusetts Highway Department (MHD). In 1985, MHD retained Bechtel/Parsons Brinkerhoff (B/PB) as management consultant. Bechtel/Parsons Brinkerhoff is a joint venture of Bechtel Corporation and Parsons, Brinkerhoff, Quade & Douglas, Inc. In 1997, the Massachusetts Legislature directed that management of the project be transferred to the Massachusetts Turnpike Authority (MTA). A year later, MTA combined key B/PB personnel with MTA staff in an *Integrated Project Organization*. In December 2007, the Integrated Project Organization was disbanded, and the CA/T was turned over to the MTA for operation and maintenance. Throughout this report, "MTA" and "owner" are used interchangeably to indicate the entity that owns, operates, and maintains the CA/T and the remainder of the MHS, except where system elements are known to be owned by others.

More than 120 consulting firms participated in the design of the CA/T, and more than 50 contractors held one or more general construction contracts. At a current cost of approximately $14.6 billion, the CA/T is the largest public works project in US history.

Sumner Tunnel. The William H. Sumner Tunnel opened in 1934 and was the first underwater crossing connecting East Boston and Boston. The tunnel, which was constructed using the shield-driven tunneling method, measures over 30 feet in diameter, has an overall length of over a mile, and accommodates two lanes of traffic. The nominal 435- and 410-foot-long concrete box sections located at either end of the tunnel were constructed utilizing the open cut and cover method. The suspended ceiling of the tunnel, which forms the exhaust ventilation plenum, was first replaced in 1959–1962 and again in 1996–1997. The Summer Tunnel is served by its own two ventilation buildings while. Operations and control is provided from the CA/T operations control center.

Callahan Tunnel. The Lieutenant William F. Callahan Tunnel was constructed parallel to the Sumner Tunnel and opened in 1961. In 1962, the Sumner Tunnel was reconfigured to convey one-way traffic westbound toward Boston, while the Callahan Tunnel carried eastbound traffic traveling to East Boston. The Callahan Tunnel is over 30 feet in diameter and just under a mile in length. The nominal 60- and 180-foot-long concrete box sections located at either end of the tunnel were constructed utilizing the open cut and cover method. The ceiling of the tunnel was replaced in 1991–1992. Like the Sumner, the Callahan Tunnel is served by its own ventilation buildings, with similar life safety systems. Operations and control is provided from the CA/T operations control center.

CANA Tunnel. The Central Artery North Area (CANA) Tunnel is composed of parallel below-grade structures that were constructed in the early 1990s in preparation for the CA/T project. The two, two-lane tunnel structures provide access between northbound and southbound Route 1 and I-93 in Charlestown.

The northbound and southbound tunnels are approximately 1,000 feet long, with an additional single-lane ramp merging into the southbound tunnel. Designed in 1987, the structures are reinforced concrete box sections of variable widths constructed by the cut and cover method. Separate exhaust and supply plenums are provided and like the Sumner and Callahan tunnels, operations and control is provided from the CA/T operations control center.

Boston Extension and Prudential Tunnel. The Boston Extension is an integral portion of the Massachusetts Turnpike that includes the portion of I-90 from the Route 128 interchange in Weston to the downtown interchange with I-93. This approximately 11.5-mile-long section of roadway was opened in 1964 and incorporates a variety of MTA facilities including bridges, walls, roadway lighting, signs, interchanges, toll plazas, pump stations, fan rooms, and the Prudential Tunnel. The approximately 3,200-foot-long Prudential Tunnel was constructed from the mid-1960s to the early 1980s through the addition of contiguous bridge and building structures over the Boston Extension. Operations and control of the Boston Extension, including video monitoring and an integrated project control system, is provided from an operations and control center.

Physical Scope of Safety Review

Phase II Scope. The physical scope of the Phase II safety review includes the structural and life safety systems of the MHS as described above.

On-Grade Elements. On-grade elements of the MHS are excluded from the safety review. However, it was agreed to include inspection of overhead signs, luminaires, traffic signals, and similar structures along at-grade elements of the MHS.

CA/T Elements Built for Outside Agencies. In general, CA/T construction contracts were administered by the MTA and B/PB, and the facilities, when complete, were to be turned over to the MTA. The CA/T project intersected with several facilities owned and operated by outside agencies, including the Massachusetts Bay Transportation Authority (MBTA), Massachusetts Port Authority (Massport), the Massachusetts Highway Department (MHD), and various utility companies. For purposes of delineating the physical scope of the safety review, the improvements for outside agencies in intersecting areas are divided into two classifications: 1) facilities designed and built under the direction of the MTA and B/PB, and 2) facilities designed and built under the supervision of outside agencies. In the second case, the construction work for the portion of the intersecting work to be turned over to the outside agency was administered by them, even though both portions of the intersecting area were constructed by a single general contractor engaged by the MTA. Facilities in the second category are excluded from the scope of this safety review. Examples include MBTA station improvements at Logan Airport, Aquarium Station, and South Station.

In other areas of the MHS, outside of the CA/T, the in-scope elements typically included readily accessible structures owned by the MTA. However, structures owned by third parties were also inspected if there is a possibility of the structure significantly impacting Turnpike operations. All of these structures are owned by parties other than the MTA.

SAFETY REVIEW TEAM

The organizational structure of the stem to stern safety review is shown below in Figure 1. The following paragraphs describe the safety review team members and external oversight groups.

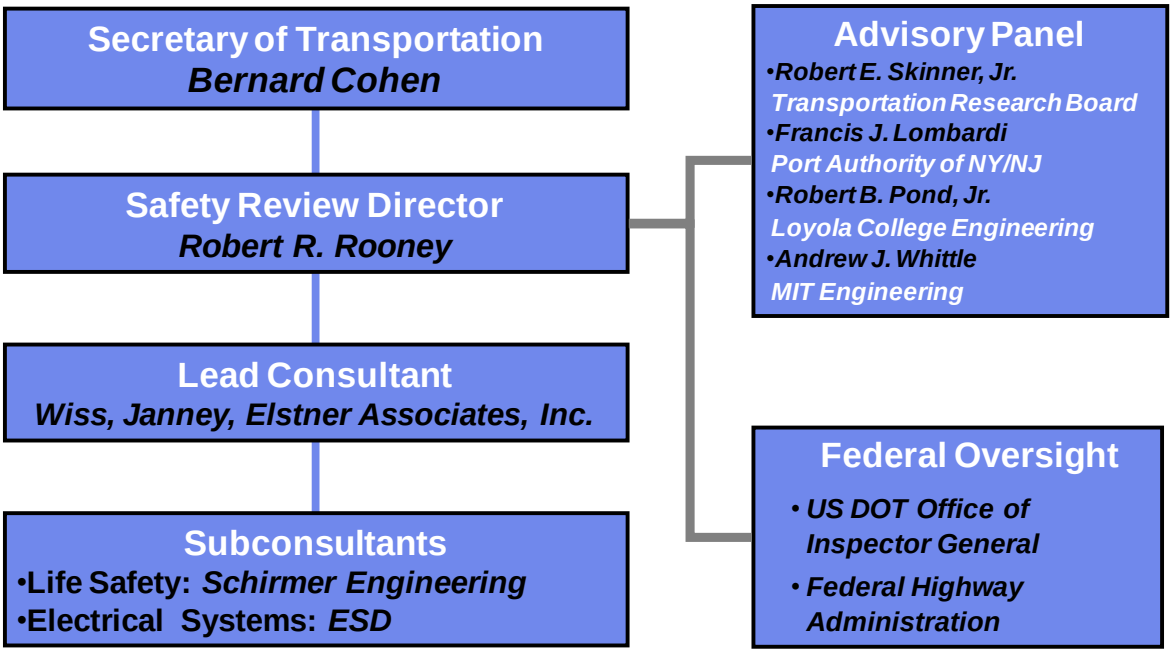

Figure 1. Organizational structure for stem to stern safety review

Robert R. Rooney, Safety Review Director. Mr. Rooney, Deputy Secretary of Transportation, was appointed by Transportation Secretary Bernard Cohen to serve as safety review director and manage the safety review project. He oversaw the activities of the consultants and served as EOT liaison to the MTA. Mr. Rooney also served as liaison to the Federal Highway Administration and the Office of the Inspector General for the US Department of Transportation, as well as the Advisory Panel.

Advisory Panel. Experts in construction, engineering, and transportation comprised the four-member panel:

- Robert E. Skinner, Jr., PE (Chairman), Executive Director of the Transportation Research Board
- Francis J. Lombardi, PE, Chief Engineer of the Port Authority of New York and New Jersey
- Robert B. Pond, Jr., PE, PhD, Chair of the Engineering Science Department at Loyola College
- Andrew J. Whittle, PE, PhD, Professor of Civil and Environmental Engineering at the Massachusetts Institute of Technology

The members of the panel provided advice through the safety review director as they deemed necessary to ensure that the safety review was thorough, objective, and effective.

Lead Consultant, Wiss, Janney, Elstner Associates, Inc. WJE, headquartered in Northbrook, Illinois, carried out the structural safety review and engaged subconsultants to conduct the life safety systems review. Gary J. Klein, PE, served as project manager. In this role, Mr. Klein oversaw all technical aspects of the safety review, coordinated the WJE team, and directly supervised the structural safety review. As principal-in-charge, William J. Nugent, PE, provided additional oversight and was in charge of project staffing. Douglas D. Crampton, PE, served as deputy project manager. Mr. Crampton led the field teams and assisted with project administration. The MHS was subdivided by physical scope (Boston Extension, concrete viaducts, etc.). An experienced WJE team leader was assigned to lead the structural investigations of each area.

Life Safety Systems Subconsultant, Schirmer Engineering Corporation. Schirmer Engineering, also headquartered in Northbrook, Illinois, was responsible for the safety review of the life safety systems, including technical oversight of the electrical/mechanical subconsultant, Environmental Systems Design. Robert Carasitti, PE, served as Schirmer project manager and Carl Baldasarrra, PE, served as principal-in-charge.

Electrical/Mechanical Subconsultant, Environmental Systems Design, Inc. Headquartered in Chicago, Illinois, ESD was responsible for evaluation of electrical and mechanical systems that support critical life safety systems. Mahmood Akhter, PE, served as ESD project manager and Kurt Karnatz, PE, served as principal-in-charge.

External Agencies. Two external agencies monitored and provided input to the safety review: the Office of the Inspector General (OIG) for the US Department of Transportation and the Federal Highway Administration (FHWA). The scope of the OIG reviews was limited to the CA/T elements of the MHS. Likewise, FHWA oversight focused on the CA/T, although they occasionally provided comments related to other elements of the MHS. These agencies attended monthly status briefings on the project. In addition, the OIG arranged for engineers from the US Army Corps of Engineers (USACE) to directly observe and selectively participate in the review activities. Led by Dick Carlson, PE, and Scott Acone, PE, USACE engineers with appropriate technical expertise were assigned to one or more project teams. They maintained contact with the team leaders and often accompanied WJE and Schirmer crews during their physical inspections. Furthermore, the FHWA and OIG/USACE teams provided comments on draft stem to stern reports and interim findings related to the CA/T, but they did not have the opportunity to review final Phase II reports.

SAFETY REVIEW APPROACH AND METHODOLOGY

Approach and Schedule

Phase I of the Stem to Stern was carried out in the fall of 2006 in five basic steps:

1. Divide the physical scope of the CA/T project into distinct categories based on initial planning and reconnaissance.
2. For each category, prioritize the physical elements and systems according to their importance to safety. Develop a work plan based on this prioritization.
3. Carry out the work plan focusing on the elements most critical to safety.
4. Analyze the data from execution of the work plan and develop review findings and recommendations.
5. Prepare a report describing the review procedure, findings, and recommendations, including a draft scope for Phase II.

Phase II of the Stem to Stern officially began in July, 2007, after comments were received on the Phase II scope. As a precursor to Phase II, some of the concerns identified in Phase I were further investigated under Phase IA, including certain high-priority safety issues as well as items for which the scope of Phase II investigation was not fully defined.

The Phase II scope is divided into four areas, as follows:

1. Follow-up of Phase I investigation of MHS (by physical scope area)
2. Special studies related to Phase I findings:
   - Incomplete tendon grouting
   - Concrete overlays
   - Pattern cracking
   - Fire performance of adhesive anchors
   - Tunnel leaks
   - Building leaks
   - CA/T ventilation systems
3. Other MHS Facilities (not included in Phase I):
   - I-90 Boston Extension (to MA-128)
   - Sumner, Callahan, and CANA tunnels (except ceiling systems)
4. Consulting on implementation of recommendations from Phases I, IA, and II:
   - Monitoring of the implementation plan
   - Technical consulting
   - Review of inspection and operations manuals
   - Independent verification of repairs and retrofits

The reports issued under the first three scope areas are listed in the introduction to this report. Findings related to the fourth of scope area, consulting on implementation recommendations, were issued in the form of e-mail messages and brief summary reports on implementation inspections and reviews.

Field work related to the Phase II scope was carried out in two primary campaigns. The follow-up investigations of CA/T facilities and initial investigations of structures along the Boston Extension were conducted during a six-week campaign from September through mid-October, 2007. Due to difficulties in making arrangements for access to railroad structures along the Boston Extension, field inspections of railroad structures were postponed until March, 2008. During this second field campaign, inspections to

verify the status of repairs and retrofit pursuant to Phase I recommendations were also conducted. Additional verification inspections were carried out in June 2008. At other times throughout the duration of Phase II, the stem to stern team was involved in reduction of field data, laboratory testing, analyses of structural and life safety systems, and reporting of findings.

Work Plan Development and Execution

Initial Planning

The work plan development and execution in Phase II was similar to that of Phase I. Based on initial review of the relevant record drawings and field reconnaissance, each team leader developed a general understanding of the following:

- The nature and extent of the structural (or life safety) systems
- The approach to the design
- The physical conditions and access limitations
- The logistics and staffing needed to meet the project objectives

Prioritization

Based on information gathered during the initial planning activities described above, key structural and life safety elements were identified and assigned a priority rating based on the *relative* likelihood of failure in the near term, and the consequences of failure. For life safety elements, failure of a system or feature generally presupposes a concurrent emergency event such as a car fire. Priorities were assigned as follows:

Priority 1

- Structural Priority 1 elements are those whose failure in the near term is more likely than that of common or typical elements, and whose failure would have a high probability of rendering the affected structure hazardous to users or employees in the general vicinity. These elements include non-redundant members and components (any member or component whose failure is likely to result in partial or complete collapse), members or components that are potentially unstable or vulnerable to buckling, connections and details that address unique or unusual conditions, and members or components currently exhibiting signs of failure or distress.
- Life Safety Priority 1 elements are those which are deficient in capability relative to the design basis or current standard performance objectives and therefore represent a significant risk to the life and limb of the public, employees, and responding emergency personnel. They also include systems and features that do not have robustness or appreciable factors of safety and whose failure represents a significant life safety risk. Non-standard systems or features that address unique or unusual conditions, as well as systems exhibiting distress or failure, are also included.

Priority 2

- Structural Priority 2 elements are those structures whose failure is relatively unlikely in the near term or whose failure is not likely to be immediately hazardous, including redundant members and components (any member or component whose load is shared by adjacent members or components such that local failure is not likely to result in collapse). Elements vulnerable to structural deterioration or other conditions representing a long-term safety concern were also categorized as Priority 2.

- Life Safety Priority 2 elements are those that have some level of redundancy and appreciable factor of safety, including systems and features that are not in full compliance with specific standards or recommend practices but have the capability to achieve performance objectives established as the basis of design.

Priority 3. Priority 3 elements are structural and life safety components whose performance is not important with regard to safety. Priority 3 structural elements include members and components whose structural adequacy is readily apparent from cursory observation, or life safety systems and features that do not have a significant impact on the overall level of safety.

The Phase II work plan consisted of assessment of Priority 1 and Priority 2 structural elements and follow-up on reportable conditions found in Phase I. Specific activities are described below under findings.

Reportable Conditions

Safety concerns (or simply conditions of interest) that arose were recorded as *reportable conditions*. Areas of interest that were judged to be safe based on visual inspection or limited document review were not recorded as reportable conditions. Examples of reportable conditions include members exhibiting distress or deterioration, apparent safety-related construction deficiencies, and other safety-related conditions that required detailed investigation. Reportable conditions were assigned a priority as described above, and the work plan was amended as appropriate to incorporate those conditions.

Concerns related to long-term deterioration and the associated impact on long-term safety were designated as Priority 2. Some reportable conditions were classified as Priority NS, that is, a condition that is not related to safety but may be of interest to the owner with respect to performance, serviceability, or maintenance.

In Phase I, the findings on reportable conditions were classified as follows:

- IC: Immediate or dangerous condition (such conditions were immediately reported to the MTA)
- R1: Remediation recommended as soon as possible
- R2: Remediation recommended in coordination with near-term maintenance and capital improvement programs
- PII: Phase II Investigation recommended to confirm or resolve concern
- MR: Monitoring recommended; consider remediation if condition worsens
- NA: No follow-up under stem to stern safety review

The same classifications were used in Phase II; however, two additional classifications were added:
- CR: Phase II follow-up work resolved concern
- MI: Item that requires regular maintenance and/or remediation

The classification of a maintenance item (MI) was created because it was often found during the implementation verification work that even after a condition was addressed, there were other new locations where the same condition was observed. The maintenance item (MI) classification is not intended to replace the original reportable condition classification of an IC, R1, or R2, but is intended to convey that a specific reportable condition should be expected to reoccur at the original location or at

another location. A reportable condition classified as a maintenance item (MI) should retain the degree of urgency of the original recommendation/classification.

Limitations of Safety Review

The stem to stern safety review endeavored to identify and assess the most safety-critical elements of the MHS. Several limitations are inherent in this type of post-construction safety review:

- Considering the vast physical scope and considerable complexity of the MHS, the review approach necessarily required making judgments as to which elements were critical to safety. Assessment of every element of the physical scope was neither possible nor appropriate. As such, assessment of the safety of the existing construction was based on evaluation of selected items.
- In any completed structure or system, it is not possible to examine and assess concealed elements such as the outside of tunnel walls, reinforcement embedded in concrete, or buried conduit.
- The safety review relied on the available project specification, or other project documents, to determine the properties of the various construction materials or life safety system components.
- The safety review relied on the available construction records. The available record drawings were reasonably complete, but did not necessarily reflect actual as-built conditions. Most CA/T project records were stored off site in warehouses. Requested project records were not always available. When such records were available, the reviewer generally did not endeavor to independently verify the accuracy of these records.
- Finally, this review is limited to structural and life safety systems. Evaluation of other risks, such as those associated with traffic flow and security threats, is beyond the scope of this review.

Nonetheless, we believe the review approach was sound and the work plan sufficiently thorough to enable WJE and its subconsultants to express a reliable independent opinion as to the safety of the structural and life safety systems, as described below and in subsequent volumes of this report.

SUMMARY OF FINDINGS

Overview

Structural and life safety systems of the Central Artery/Tunnel were designed using appropriate modern standards. In general, these systems are robust and, where appropriate, redundancy is provided. The designs of the older elements of the MHS appear to be consistent with the standards of the period, although detailed design criteria were not available. The level of distress and deterioration in these older structures is consistent with their age and exposure.

Nonetheless, several structural deficiencies and concerns exist that could affect near-term or long-term safety, as described in the subsequent sections of this report. Some of these conditions were uncovered by the stem to stern review; others were at least partially known in advance of this study and were subsequently investigated under this review. The following table summarizes the recommendations according to the classifications described above under *Reportable Conditions*.

Table 1. Summary of Phase II Reportable Conditions[1]

MHS Facility	IC	R1	R2	MR	Totals
Central Artery/Tunnel: Phase I Follow-up[2,3]	0	4	10	30	44
Central Artery/Tunnel: New Phase II Items[3]	6	3	3	0	12
Sumner / Callahan / CANA Tunnels[3]	1	10	24	3	38
Boston Extension / Prudential Tunnel[3]	42	42	37	10	131
Subtotals / Grand Total	49	59	74	43	225

1. Counts tabulated at time of Summary Report issuance, which may not reflect resolution of all comments from the OIG and FHWA.
2. Based on the items identified for follow-up work in Phase II. In addition, 18 items were classified as Concern Resolved (CR).
3. Note some reportable conditions may have received multiple recommendations and/or occur in multiple locations.

The following sections describe the most notable deficiencies and concerns. To allow for comparisons among the various MHS facilities, the safety concerns are discussed by category:

- Tunnel ceiling supports
- Immediate safety hazards
- Structural capacity concerns
- Long-term threats to structural safety
- Life safety systems

Tunnel Ceiling Supports

The emergency legislation leading to this stem to stern review was prompted by a collapse of several ceiling panels in the I-90 Connector tunnels on July 10, 2006. The collapse occurred when adhesive anchors connecting the ceiling hanger rods to the roof structure pulled out. Table 2 shows the construction

details and conditions in each of the tunnels with ceilings suspended from hanger rods. (The lightweight ceiling panels in the CANA tunnel are directly attached to the underside of the concrete roof and thus are not included in the Table 2.)

Table 2. Ceiling Support Data

Tunnel (Year Ceiling Installed)	Ceiling Panels		Ceiling Attachment		Adhesive Anchors			
	Type	Wt.	No. of Hangers	Attachment Type	No. per Hanger	Dia.	Design Embed	Adhesive
I-90 Connector (1999-2000)	4-in. normal-weight concrete	50 psf	10,800[1]	Bolts in embedded steel channels, typical	NA			
			1,300[1]	Adhesive anchors at east tunnel portals and isolated locations	2 or 4	5/8"	5 1/2"	Epoxy resin: Power-Fast®
I-90 Ted Williams (1994-1995)	2-in. composite: lightweight concrete core with enameled steel face sheets	20 psf	12,700[2] 5,400[3]	Adhesive anchors	2 (typ)	3/4" (typ)[6]	5 1/2"	Epoxy resin: UltraBond® and Epcon®
I-93 Central Artery (2001-2002)	4-in. normal-weight concrete	50 psf	12,800	Hanger plates are typically attached to steel roof girders. In limited areas at ramps, hanger plate connections are welded to embedded plate inserts in concrete roof slab.	NA			
			55[4]	Adhesive anchors at tunnel section under MBTA Red Line	2	1"	22"	Vinyl ester resin: Hilti HVU®
Sumner Tunnel (1996-1997)	2-in. composite: lightweight concrete core with enameled steel face sheets	15 psf	2,739[5]	Adhesive anchors (frequently installed in spalled and delaminated concrete)	1 (typ)	3/4"	6 5/8"	Polyester resin: Keligrout ® 101
Callahan Tunnel (1991-1992)	2-1/4-in.composite: mineral board with enameled steel face sheets	15 psf	2,338[5]	Adhesive anchors (and steel welding)	1 (typ)	3/4"	6 5/8"	Epoxy resin: Foil-Fast Epoxy® and Polyester Resin: Lokset Anchorbond®

1. I-90 Connector totals include Ramp DN ceilings installed by Contract C17AA.
2. Total includes 10,000 hangers, 2,700 daigonal braces.
3. Estimated number of anchors securing direct-attached ceiling framing to roof.
4. Number of upper hanger plate connections to concrete roof structure.
5. Total including diagonal braces
6. 5/8", 1", and 1 1/4" also used

With respect to the ceiling support systems, no noteworthy structural deficiencies were identified at the I-93 Central Artery Tunnel or the CANA Tunnel. Following the collapse in the I-90 connector, the ceiling system was analyzed and retrofitted using undercut mechanical anchors, resolving the safety concern. Accordingly, a Phase II investigation of ceiling systems focused on adhesive anchors in the Ted Williams, Sumner, and Callahan tunnels.

Ted Williams Tunnel Anchors

As a follow-up to concerns identified in Phase I, several Phase II tasks relating to the Ted Williams Tunnel ceiling systems were performed: review of additional construction records that had not been reviewed in Phase I; review of tests and inspections of ceiling anchors performed following conclusion of the Phase I review; and supplemental structural analyses of the ceiling system. In addition, WJE and

Schirmer Engineering conducted a special study to predict and quantify the performance of epoxy anchors in the Ted Williams Tunnel ceiling system when exposed to elevated temperatures during a tunnel fire.

In service to date, most of the epoxy anchors have not exhibited indications of susceptibility of creep under sustained loads. Nevertheless, the long-term creep performance of the existing anchors remains in question. One of the two epoxy adhesives used in the original ceiling installation has not undergone creep testing, and its manufacturer does not recommend its use for sustained load applications. Short-term creep tests performed in 2006 of two anchors in the Ted Williams Tunnel were not conducted over a sufficiently long duration to provide conclusive results. Similarly, available data from anchor pull tests, including proof tests during construction and limited proof testing performed in 2006, are inadequate as a basis for assessment of in-situ anchor reliability in terms of ultimate tensile capacity. For these reasons, a more extensive and rigorous program of creep testing and ultimate load pull testing of the existing epoxy anchors is recommended. Volume II-3 provides the details of the recommended test program, along with criteria for acceptance of the anchors based on the test results.

The structural design of the direct-attached ceilings, located in the portal regions and other localized areas of the Ted Williams Tunnel, renders the epoxy anchors effectively inaccessible for visual inspection. In absence of a practical, cost-effective means to inspect and monitor these epoxy anchors, it is recommended that the direct-attached ceilings be retrofitted by adding either external supplemental stringers or by their removal. A conceptual retrofit design, illustrated in Figure 2, has been developed and provided.

The special study of the fire resistance of the Ted Williams Tunnel anchors was based on a heat release rate of 30 megawatts, consistent with the provisions of the 2004 edition of NFPA 502. Heat exposures were quantified for worst-case conditions using a computer-based simulation of gas flow in the tunnel and exhaust plenums (Figure 3). Thermal and structural behavior to the typical epoxy anchors were predicted using an Abaqus finite element computer model. For modeling purposes, selected thermal and mechanical properties were determined by a series of tests of epoxy materials at elevated temperatures.

The elevated temperature performance of Epcon epoxy (one of two products used in the ceiling installation) was far superior to that exhibited by Ultrabond (the other installed epoxy product); the worst-case response of the ceiling anchors is therefore governed by the performance of the Ultrabond material. The Abaqus model results indicate that anchor failure could occur in the vicinity of the fire origin in a fire of the considered magnitude and duration. Because the stringers supporting the Ted Williams Tunnel ceiling are continuously spliced at joints between structural modules, initial failure of a limited number of anchors could lead to progressive collapse of additional anchors over a larger area. As such, the stem to stern recommends review and revision of emergency response procedures as necessary to reflect the possibility of a ceiling collapse progressing to areas beyond the immediate vicinity of the fire origin. Furthermore, selected retrofits of the ceiling system are recommended to mitigate the risk of progressive collapse during fire, assuming the results of recommended in-situ tests indicate acceptable reliability of the adhesive anchors under ambient temperature conditions. Specifically, the bolted splice should be replaced with a slip connection, as shown in Figure 4.

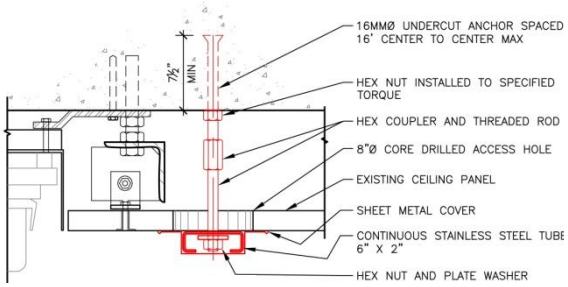
16MMØ UNDERCUT ANCHOR SPACED 16" CENTER TO CENTER MAX
7½" MIN
HEX NUT INSTALLED TO SPECIFIED TORQUE
HEX COUPLER AND THREADED ROD
8"Ø CORE DRILLED ACCESS HOLE
EXISTING CEILING PANEL
SHEET METAL COVER
CONTINUOUS STAINLESS STEEL TUBE 6" X 2"
HEX NUT AND PLATE WASHER

Figure 2. Conceptual design for direct-attached ceiling retrofit supports

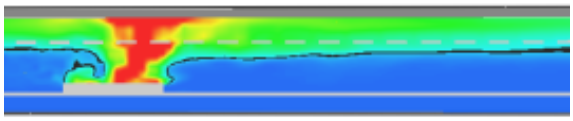

Figure 3. Computer-based simulation of gas flow in the tunnel and exhaust plenums

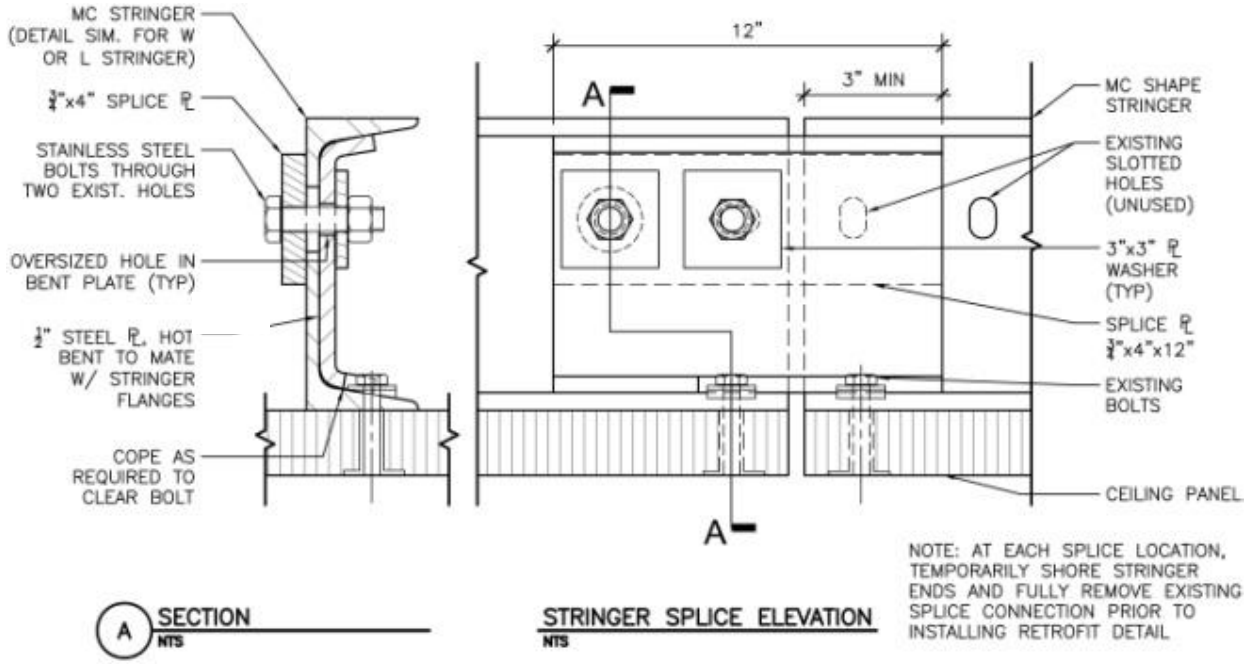
MC STRINGER (DETAIL SIM. FOR W OR L STRINGER)
¾"x4" SPLICE PL
STAINLESS STEEL BOLTS THROUGH TWO EXIST. HOLES
OVERSIZED HOLE IN BENT PLATE (TYP)
½" STEEL PL, HOT BENT TO MATE W/ STRINGER FLANGES
COPE AS REQUIRED TO CLEAR BOLT
12"
3" MIN
A
A
MC SHAPE STRINGER
EXISTING SLOTTED HOLES (UNUSED)
3"x3" PL WASHER (TYP)
SPLICE PL ¾"x4"x12"
EXISTING BOLTS
CEILING PANEL
NOTE: AT EACH SPLICE LOCATION, TEMPORARILY SHORE STRINGER ENDS AND FULLY REMOVE EXISTING SPLICE CONNECTION PRIOR TO INSTALLING RETROFIT DETAIL
A SECTION NTS
STRINGER SPLICE ELEVATION NTS

Figure 4. Conceptual design for retrofit of stringer splices

Sumner Tunnel Anchors

In Phase I, it was discovered that the condition of the Sumner Tunnel liner compromised the anchors; many anchors were installed where the liner was spalled and delaminated, reducing the effective embedment depth (Figure 5). In Phase II, WJE conducted further tests on the tunnel liner and reviewed the work performed by MTA's consultant on the tunnel anchors. While proof tests (at low loads) of anchors in suspect concrete were successful, five of fifteen bolts installed in sound concrete in the Sumner Tunnel liner failed at a proof load of 8,125 pounds, about twice the design load. This failure rate, which does not account for long-term load effects, is exceedingly high and may indicate strength degradation or installation anomalies. Accordingly, it is recommended that all adhesive anchors supporting the existing ceiling system be replaced as part of a long-term liner repair program. In the meantime, comprehensive systematic and regular re-inspection of the liner, anchors, and ceiling components is recommended at an interval not to exceed six months.

Figure 5. Anchor in Sumner Tunnel installed into spalled area of concrete liner, resulting in reduced embedment

Figure 6. Gap between yoke and concrete liner in Callahan Tunnel.

Callahan Tunnel Anchors

Unlike the anchors in the Sumner Tunnel, the anchors in the Callahan Tunnel frequently exhibit gaps between the yoke and concrete liner (Figure 6). While some of these gaps may be due to fit up, the majority are believed to be due to creep-related deformation and slippage of the epoxy adhesive. Although the Callahan Tunnel anchors performed well in recent short term proof tests, the observed behavior indicates a likely deficiency in long-term creep resistance of the epoxy. The epoxy used in the Callahan Tunnel is of similar manufacture to that used in the I-90 connector tunnel, where epoxy failure led to the partial ceiling collapse in July 2006. As such, WJE recommends complete replacement of the anchorage system in the Callahan Tunnel within the next one to two years. Until repairs are initiated, comprehensive inspections of the anchors and ceiling components are recommended at an interval no greater than six months.

Discussion of Adhesive Anchor Performance

If there is a commonality among the performance of adhesive anchors in the Ted Williams, Sumner, and Callahan tunnels, it is the high degree of variability and unpredictability. The recent testing revealed a vast discrepancy in the fire resistance of the two epoxy formulations used in the Ted Williams Tunnel. The Sumner Tunnel anchors exhibit good performance in spite of being installed in spalled and delaminated concrete, yet several of the Sumner Tunnel anchors failed the recent proof tests. On the other hand, the Callahan Tunnel anchors exhibit slip, but performed well in recent proof tests.

This variability undermines confidence in long-term performance of adhesive anchors. Accordingly, replacement of the adhesive anchors in the Sumner and Callahan tunnels has been recommended. Furthermore, additional creep and pull-out testing of the Ted Williams Tunnel anchors is recommended before they are accepted for long-term use. Fortunately, the ceiling systems are capable of redistributing loads in the event of individual anchor failures. Diligent inspections and as-needed retrofits will ensure safety in the short term until long-term recommendations are implemented.

Prudential Tunnel – Suspended Slab

In a portion of the Prudential Tunnel, a suspended cast-in-place concrete slab serves as the tunnel ceiling. As can be seen in Figure 7, the concrete was found to be deteriorated, compromising the strength of the rod-to-slab connection. Fortunately, a structural analysis showed that the system is sufficiently redundant to preclude progressive collapse in the event of failure of any one hanger. In late 2007, the owners of the Hynes Convention Center engaged an engineering firm to investigate the suspended tunnel slab. Their report recommended both near-term and long-term repairs, as well as supplemental studies. The stem to stern review concurs with these recommendations.

Figure 7. Deterioration in the vicinity of embedded steel plates supporting a suspended slab

Immediate Safety Hazards

As in Phase I, the Phase II safety review uncovered several conditions related to structural systems that were judged to be unsafe and warranted immediate follow-up action. These conditions did not relate to integrity of primary structural systems; rather, most immediate safety concerns related to loose or unsound concrete over traffic, or fractured or damaged metal poles.

Loose or Unsound Concrete over Traffic

In Phase I, numerous locations of unsound concrete and insipient spalls were identified along the underside of the concrete roadway ceiling near the portals and below ventilation buildings of the Sumner Tunnel. Similar conditions were found in the Callahan Tunnel in Phase I, but to a much lesser extent. Pursuant to stem to stern recommendations, the unsound concrete in the Sumner and Callahan tunnels has been addressed with ongoing inspection and maintenance, mainly the removal of loose concrete.

Loose overhead concrete was also discovered in certain CA/T tunnels and concrete viaducts in Phase I. The unsound concrete generally related to construction deficiencies and patches installed during construction. A detailed study of patches on the underside of concrete viaducts undertaken in Phase IA revealed that the patches were generally sound and did not pose an immediate concern.

In Phase II, loose overhead concrete was discovered in several locations along the Boston Extension. Most frequently, the loose concrete occurred along the exterior stringers and overpasses, where corrosion at the flange edge caused delamination and spalling along the edge of the concrete deck. Damage was also

observed where moisture and salts had penetrated through the bridge deck. Examples of these types of distress can be seen in Figures 8 and 9.

Figure 8. Spalling and unsound concrete along edge of deck

Figure 9. Spalling and delamination of deck soffit due to penetration of moisture and salts through deck

Additionally, reinforced concrete pier caps were frequently spalled or delaminated due to corrosion of embedded reinforcement. The spalled and deteriorated concrete conditions have developed over many years, and represent a deterioration mechanism that is common to the transportation infrastructure. Nonetheless, the relatively high frequency of such conditions occurring along the Boston Extension suggests that more intensive inspection and maintenance are needed to mitigate the hazard.

Damaged Metal Poles

In Phase I, inspection of 2,800 of the 3,500 sign, luminaire, and traffic signal poles in the CA/T revealed that several were unsafe due to vehicular impact, original construction deficiencies, and corrosion. In Phase II, the remaining 700 CA/T metal poles were inspected, and welds and anchorage rods for the high mast towers were investigated using non-destructive testing methods (Figure 10). No deficiencies were identified in the high mast towers, but several smaller were found to be structurally deficient. In particular, impact damage to several poles was noted.

Also, in Phase II, the metal poles along the Boston Extension were inspected. In addition to structural deficiencies related to impact damage and original construction deficiencies, advanced corrosion of some of the older poles was observed. An example is shown in Figure 11.

Figure 10. Ultrasonic testing of high mast lighting tower

Figure 11. Light pole exhibiting rust holes due to corrosion

Structural deficiencies in metal poles, especially damage due to vehicular impact, will be an ongoing problem. Of the 3,500 poles in the CA/T, 54 required repair or retrofit. In half of those cases, the construction deficiency was considered dangerous, requiring an immediate repair. Future damage can be expected from corrosion and vehicular impact. As such, the stem to stern safety review recommends that all metal poles be included as part of the regular inspection and maintenance program. It is our understanding that only tall-mast lighting and overhead sign structures are currently included in the MTA's inspection program.

Structural Capacity

Central Artery/Tunnel

The Phase I investigation uncovered several structural concerns that warranted further investigation in Phase IA and Phase II. Examples include the following:

- Inclined cracks in reinforced concrete pier caps
- Cracking of the Zakim Bridge pylons (Figure 12)
- Anchor plate deformation at the main span stay cable anchors at the Zakim Bridge (Figure 13)
- Cracking at tunnel portals (Figure 14)

In addition, the seismic resistance of several elements was questioned, including the following:

- The slender CMU shear walls between level 3 and the roof of Ventilation Building 1
- The lateral load resisting system of the Spectacle Island Visitor Center
- Unintended interference during a seismic event at the tall pier column (Bent CT1), as shown in Figure 15

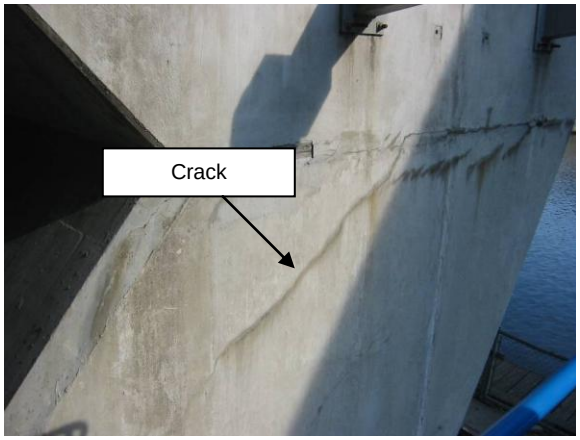

Figure 12. Cracking at south tower east leg of Zakim Bridge

Figure 13. Anchor plate deformation at bottom main span stay cable anchor, Zakim Bridge

Figure 14. Diagonal cracking in portal beam at Ted Williams Tunnel I-90 Eastbound west portal

Figure 15. Seismic interference at concrete pier columns, Bent CT1

Additional investigation work to resolve structural capacity concerns in Phase IA and II included site inspection, non-destructive testing to locate internal reinforcement, and structural analyses. Generally, these studies resolved structural capacity concerns. Likewise, review of seismic design criteria and analytical evaluation of the seismic concerns indicated that the design criteria were conservative and the structures in question were adequately designed for the anticipated seismic event.

However, these follow-up studies identified a structural deficiency of a pier supporting the Leverett Bridge. As shown in Figure 16, the pier cap is diagonally cracked between the west pier column and west bearing. Detailed structural analyses following traditional section design approaches as well as strut-and-tie modeling revealed that the nominal capacity was less than required by the design specifications (1992 AASHTO *Standard Specifications for Highway Bridges*). Of particular concern were future lane closures that increase the lateral eccentricity of live load and the bearing reaction at the corner of the bridge. However, these analyses also showed that the structure was safe for normal traffic.

Strengthening is recommended to assure long-term structural integrity. Specifically, installation of grouted reinforcing bars inserted from the underside of the cap beam across the observed crack is

recommended, along with similar strengthening on the east side of the cap beam. Also, sealing of the cold joint along the top of the cap beam is recommended to prevent further moisture intrusion into the crack. Until the crack is reinforced, changes in crack width are being monitored using potentiometers installed across a crack, as shown in Figure 17.

Figure 16. Diagonal crack at Leverett Bridge pier

Figure 17. Potentiometers used to monitor changes in crack width at Leverett Bridge pier

Sumner, Callahan, and CANA Tunnels

Other than the concerns regarding ceiling anchorage as previously described, no structural capacity concerns at the Callahan and CANA tunnels were identified in Phase I. The advanced deterioration of the Sumner Tunnel liner (Figure 18), however, raised concerns as to its structural capacity. Accordingly, additional studies of the liner condition and capacity were undertaken in Phase IA and Phase II. The circular steel and concrete liners, acting alone or together, were found to have adequate strength to safely resist the expected earth pressures and hydrostatic forces. Limited non-destructive testing of the steel liner did not uncover any indication of corrosion. The damage to the concrete liner was found to be due to chloride-induced corrosion of the embedded reinforcement. The concrete is chloride contaminated but otherwise in fair condition. Repairs to the concrete liner are recommended in conjunction with the ceiling hanger retrofits previously discussed.

Figure 18. Damage to crown region of Sumner Tunnel liner

Boston Extension and the Prudential Tunnel

The structural systems employed in the buildings and bridges spanning the Boston Extension are straightforward, but not as robust as the CA/T structures. For example, the overpass structures along the Boston Extension were designed for trucks weighing substantially less than the trucks considered in the design of CA/T structures. Furthermore, the 40-year-old structures are suffering the expected effects of exposure to the harsh northern climate. In particular, exposure to deicing salts has resulted in chloride-induced corrosion of embedded reinforcing and section loss of steel members in some areas. The most noteworthy examples of structural capacity concerns are described in the following paragraphs.

Sheraton Hotel. The precast concrete double tee framing (for the first level of the hotel structure) exhibits signs of severe deterioration and distress. This structural system, commonly employed for parking structures, has not performed well in the harsh environment. Particular concerns are as follows:

- A precast concrete ledge beam that supports the double tee floor framing has cracked and exhibits a downward movement, compromising the support of the outermost double tee stem (Figure 19).
- An existing repair channel installed adjacent to the bearing ledge does not appear to be properly anchored into sound concrete (Figure 20).
- Concrete deterioration near the ledge support stems has resulted in delamination and potential spalling, compromising the support of the double tees.

Figure 19. Distressed bearing condition at corner of precast framing

Figure 20. Existing channel repair not properly anchored to ledger beam

At the time of these discoveries, an engineering consultant for the hotel owner was preparing structural repair drawings. WJE had an opportunity to comment on the drawings, which were revised and implemented. Furthermore, shoring was immediately installed at the southeast corner of the building in view of the serious ledge beam crack observed at that location. In view of these structural concerns, the stem to stern safety review recommends that an inspection program be established to provide a formal process to monitor the condition of the precast double tee floor system and the performance of the various repairs installed in the structure spanning the roadway.

Advanced corrosion of steel stringers. Exposure to water and deicing salts has resulted in advanced corrosion in isolated cases. The most serious example is shown in Figure 21, where advanced corrosion weakened and reduced a section of a web enough to initiate a crack and allow it to propagate over the top

of the bearing area. This condition had already been discovered by the MTA, and wood blocking was installed to provide an alternate load path. The stem to stern safety review recommends that the more severe corrosion conditions be addressed in the near-term.

Figure 21. Section loss and cracking of steel stringer web above bearing, Boston Extension

Figure 22. Advanced deterioration of pier cap cantilever, Boston Extension

Deterioration of cantilevered cap beams. At a few locations, the reinforced concrete cap beams supporting bridge girders were severely deteriorated. An example is shown in Figure 22. Although not considered an immediate safety threat, an engineered repair is recommended for installation as soon as possible.

Long-term Threats to Structural Safety

Central Artery/Tunnel

In Phase I, several potential long-term threats to structural integrity were identified and further study of these conditions in Phase II was recommended.

Deterioration due to tunnel and building leaks. Special studies of leakage into tunnels and buildings indicated a variety of leakage sources. The tunnel leak study evaluated water infiltration as determined from pumping data. The current average leak rate from all known sources of water is equal to 0.003gal/sf/day, which is consistent with the most stringent published requirements for tunnel leakage.

As can be seen in Figure 23, there is considerable seasonal variation in water pump volumes, indicating that the most significant leak source is water penetrating through construction joints that open as the tunnel structures cool.

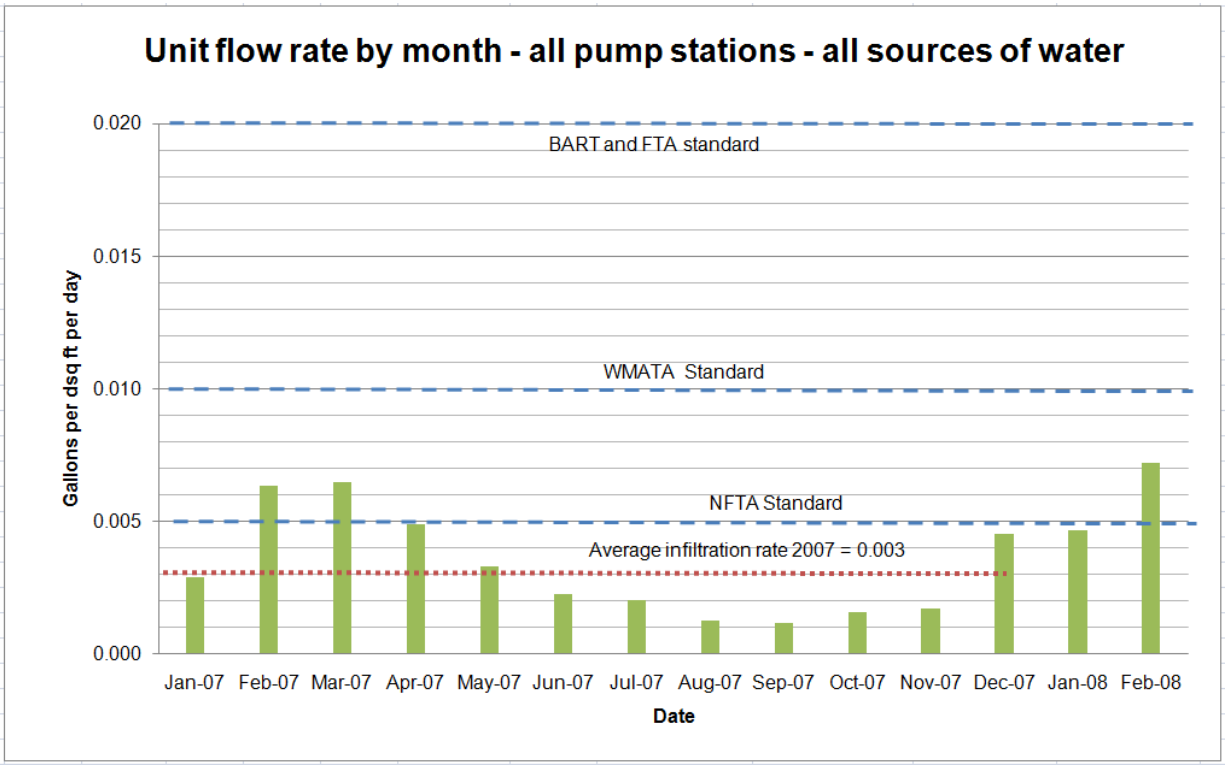

Figure 23. Seasonal nature of water pump volumes, by month, is clearly demonstrated. Volumes are divided by total tunnel surface area to obtain the above graph.

Most of the water leaking into the tunnels and buildings is high in chlorides, and one test sample exhibited high sulfate content. Chlorides exacerbate corrosion of embedded reinforcement and exposed structural steel; sulfates attack the concrete itself. As such, leaks threaten long-term structural integrity of the tunnels. Figure 24 shows evidence of previous water leakage at the tunnel roof to slurry wall interface along northbound I-93.

Figure 25 shows the preparation for a concrete repair due to leaks at a tunnel construction joint. As can be seen in Figure 26, an isolated leak in the Ted Williams Tunnel resulted in a small spall, compromising the integrity of the nearby ceiling hanger anchors. Damage of these types is expected to occur with increasing frequency. In addition to potential damage of the structural system, the leaks also threaten sensitive electrical equipment, as shown in Figure 27. Accordingly, long-term monitoring of leakage and its effects is recommended.

Figure 24. Orange staining and evidence of previous water leakage at tunnel roof to slurry wall interface in I-93 Northbound

Figure 25. Concrete removed in preparation for tunnel roof repair where a leak has caused spalling and delamination at a construction joint

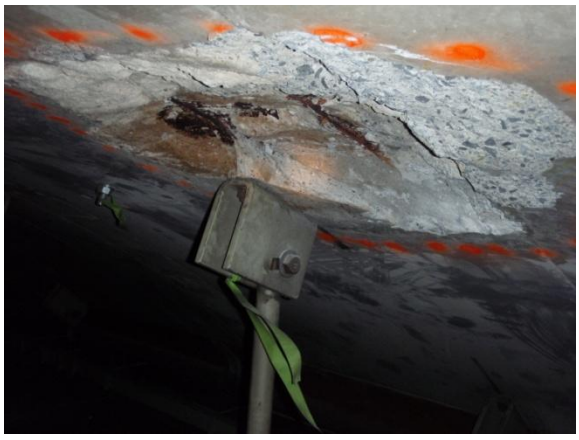

Figure 26. Spall at isolated leak in crown of Ted Williams Tunnel

Figure 27. Standing water under electrical cabinets in the main electrical room on Sub-grade Level 1 of Ventilation Building 4. Note the rusted electrical conduits.

Pattern cracking of tunnel roof structures and pier columns. During Phase I, WJE inspectors observed unusual pattern cracking in some areas of the tunnel roof structures and pier columns (Figure 28). Prior to the stem to stern review, the US Attorney and FHWA alleged that one of the ready-mix concrete suppliers used cements and aggregates that did not meet CA/T specifications and falsified delivery tickets in order to reuse concrete that was rejected because the allowed delivery time had lapsed. Further study in Phase II was recommended to determine whether or not the observed cracking is related to inferior concrete. Field observations and petrographic examination of core samples indicated that the distress is consistent with early age cracks that occurred when the concrete was still plastic. Alkali silica reaction (ASR) or other serious detrimental material problems were not identified in the areas studied; although the limited sampling does not rule out the risk of ASR at other project locations.

A separate WJE study of substandard concrete supplied to the CA/T found that the Taunton coarse aggregate has the potential for ASR.[1] Also, this study for the FHWA found that many concrete samples did not contain fly ash, a material used to mitigate ASR, or that it was only present in trace amounts. Two cores from the slurry wall (M43) that contain the Taunton coarse aggregate exhibited evidence of ASR reactions. However, the only symptom of the reaction was trace to minor amounts of ASR-gel-lined air voids. No cracking or micro-cracking that was clearly related to the ASR gel was observed. The ultimate consequence of having ASR-reactive aggregates in the concrete is difficult to predict. The ASR reaction will occur fastest in locations where the concrete is usually wet, such as the slurry walls. However, the reaction may also occur in barriers, decks, or any other structure that is exposed to moisture.

Treatment of pattern cracking at pier columns to prevent water ingress is recommended. Pattern cracking of tunnel roof slabs should be monitored, and passive cathodic protection systems to control corrosion of the uncoated reinforcing bars should be considered.

Figure 28. Patterned cracking of concrete pier column

Figure 29. Deteriorated overlay at I-90/1A interchange

Premature deterioration of concrete overlays. Project specifications require that traffic bearing surfaces on structures be protected with a rigid concrete overlay, using either microsilica or latex-modified concrete. The former was generally used. In isolated areas throughout the CA/T project, overlay deterioration was observed as indicated by delamination and cracking, as shown in Figure 29. The Phase II investigation revealed that the distress most frequently occurs along transverse construction joints in the overlay, which were intended to align with construction joints in the structural slab. Construction joints are vulnerable to cracking and delamination because bond stresses are increased at the discontinuity. Furthermore, many of the sawn joints did not align with the underlying construction joint, and the overlay failed because it could not accommodate the seasonal movement at the construction joint. The performance of the overlays on the elevated structures was generally very good, although minor cracking and debonding was observed. The overlay is the primary line of defense against moisture and chloride ingress at joints in precast segments (including those in the Zakim Bridge), where reflective cracking could lead to chloride contamination of the grout surrounding the primary post-tensioning tendons.

[1] \Paul D. Krauss, Lidia Uznanski, and Margaret Reed, *Central Artery/Tunnel Project Investigation of Substandard Concrete Supplied by Aggregate Industries, Northeast*, WJE Report 2002.3359.14, prepared for the Federal Highway Administration, Washington, DC, June 2008.

Inspection and maintenance of the overlay in these areas is recommended in the interest of long-term safety.

Incomplete tendon grouting. Post-tensioned tendon reinforcement, consisting of either multi-wire strands or threaded bars, was used in several concrete viaduct elements, particularly box girder bridges. In virtually every installation, the tendon duct was to be filled with cementitious grout after the tendons were pulled to the specified tension. The grout's purpose is to provide bond between the prestressing steel and the surrounding concrete, and to protect the steel tendon from potentially damaging conditions, particularly ingress of moisture and salts. In early 2001, the CA/T became aware of the presence of grout cavities and voids, potentially exposing the strands to oxygen, moisture, and salt. These voids were primarily a result of grout bleed water. Accordingly, the project undertook a program of inspection and regrouting using vacuum grouting techniques. However, not all tendons (or the full length of inspected tendons) were inspected. Furthermore, minor voids were permitted if the grout covered the post-tensioning strand. After thoroughly reviewing the project documents in Phase IA, WJE recommended further study in Phase II. This investigation involved additional document review, prioritization of tendons according to structural significance, cross referencing tendon structural significance with contractor inspection repair results, and structural analyses. WJE's investigation revealed that there is sufficient capacity to resist service loads, even with partial loss of post-tensioning forces as a result of strand deterioration. WJE did not identify any tendons whose failure would result in structural collapse. Routine visual inspections are critical to the assessment of tendon deterioration and are recommended. In addition, the installation of acoustic-monitoring systems at several of the more critical post-tensioned structures is recommended. These systems would serve as an early warning of strand deterioration. More extensive monitoring and more thorough inspections should be implemented if frequent wire breakage is detected.

Sumner, Callahan, and CANA Tunnels

As previously noted, the Sumner Tunnel liner is damaged due to chloride-induced corrosion of reinforcement. Likewise, the roadway structure is in need of repair. Repairs of the Sumner Tunnel liner and roadway structure are recommended.

The Callahan Tunnel is showing signs of similar deterioration. The quality of the shotcrete liner is fair to poor, and future deterioration can be expected where moisture and salts penetrate the concrete. Future repairs to the Callahan Tunnel liner and roadway structure will eventually be needed to maintain structural integrity.

The CANA Tunnel did not exhibit any unusual indications of premature deterioration that threaten long-term structural integrity. However, its environment is similar to that of the other MHS Tunnels and some level of future deterioration should be expected.

Boston Extension and Prudential Tunnel

The damage to the steel and reinforced concrete bridge structures is consistent with four decades of exposure to a harsh northern climate. Moisture and deicing salts are the primary threats to long-term structural integrity: specifically, section loss of steel members and corrosion of embedded reinforcement in concrete members. Although the structural systems are straightforward, the structures along the Boston Extension are not as conservatively designed as those in the CA/T. Accordingly, they are more vulnerable to loss of structural integrity due to exposure. As previously noted, advanced deterioration has already raised structural safety concerns in a few areas.

Life Safety Systems

Central Artery/Tunnel

The Phase II work plan consisted of evaluation of Priority 1 and Priority 2 life safety system elements that were not fully reviewed in Phase I of the audit. The review found that the design of the life safety elements are consistent with the basis of design and the provisions of NFPA 502, *Standard for Road Tunnels, Bridges, and other Limited Access Highways*, 2004 edition. However, the review revealed conditions that should be addressed by ownership in the near-term, as described below.

Automatic Fire Detection and Detection Time. Notably, the fire detection system is still not in full compliance with the project design criteria. The installation of reliable cell phone service remains incomplete; however, cell phone providers are in the process of completing the installation of cell phone repeaters in the CA/T system. Also, an upgraded version of the traffic detection system is underway, though not yet complete as of this report, although the equipment and software has been received by the MTA. As such, high priority should be given to the immediate completion of this system. With the successful installation and implementation of the video detection system, it is our opinion that the fire detection features and design fire detection time criteria will be satisfied, and will in fact provide detection features that are substantially better than originally anticipated.

Integrated Project Control System (IPCS). At the time of writing, the IPCS is not fully functioning. Software upgrades are in progress and not all systems are integrated. Completion of the planned upgrades for the system software, and the full integration of all life safety systems should be given high priority in the near term.

Maintenance Programs. The primary elements of the maintenance program are maintenance schedules, procedures, and actions covered in the preventive maintenance software module of the maintenance management information system (MMIS). The environmental issues that face the highway system are more severe than originally anticipated during the design of the tunnels and their life safety systems. The maintenance program should be continually reviewed and updated to reflect the changing needs for maintaining critical systems and features.

Emergency Response and Training Programs. Interagency coordination and cooperation must continue to be a primary and ongoing objective of the project. Routine training that involves all agencies must continue to be performed and updated to reflect "lessons learned." The training program should include variations of incidents, third party observers, and post exercise briefings and reports to refine future efforts. Specifically, the emergency response and trainings plans should also include modules on large scale fire events and the potential localized failure of the suspended ceiling systems.

Routine Reviews. Lastly, life safety protection for tunnels is continuing to evolve and mature. As new considerations are made known through the nationally recognized standards, the highway system should be reviewed against these new considerations to evaluate how the existing facilities compare and to identify future modifications that should be incorporated to maintain a high level of life safety. A new edition of NFPA 502 has been published in 2008. Future editions will be published on a three-year cycle. It is recommended that the Massachusetts Turnpike Authority develop and implement a program to reassess compliance with new developments in tunnel protection concepts and features. One possible program would be to use each new edition of NFPA 502, or the possible future Tunnel Design Guidelines proposed by AASHTO, as a basis for reassessment.

Sumner and Callahan Tunnels

The Sumner and Callahan tunnel life safety systems were evaluated in accordance with the then-current standard of care based on NFPA 502, 2004 edition. The review identified deficiencies associated with the fire detection and alarm systems, traffic control systems, standpipe systems and water supply, and portable fire extinguishers that should be addressed by the MTA in the near term.

The most significant finding relates to the emergency ventilation system and emergency egress features.

To assure that sole reliance for life safety in these tunnels is not dependent on a single system, it is recommended that the installation of a fire suppression system be considered to provide a level of life safety redundancy that does not currently exist in the Sumner and Callahan tunnels.

Furthermore, the electrical systems are antiquated. Repair and retro-commissioning is recommended.

CANA Tunnel

The CANA Tunnel and ventilation building life safety systems were evaluated in accordance with NFPA 502, 2004 edition. There are a few areas where the life safety systems do not fully comply with this standard, which is not surprising because NFPA 502 was a recommended practice and not an applicable code at the time of construction. The most important findings relate to exit spacing and communication systems. Minor concerns such as water leakage around electrical service equipment, damaged fire extinguisher brackets, and missing manual fire alarm boxes were also noted.

Prudential Tunnel

The Prudential Tunnel was a result of separate projects for several buildings constructed over the course of many years from the mid-1960s to the early 1980s, well before NFPA 502 existed. Nonetheless, the Phase II review found that the main life safety elements required by NFPA 502 have been implemented in the Prudential Tunnel system. However, not all of the required elements were present and, of those that were provided, not all were fully compliant with the standard.

Implementation of Stem to Stern Recommendations

Part of the Phase II scope of work was monitoring and consulting related to the implementation plan, when requested by the EOT. This work included technical consulting on the remediation measures for various Phase I reportable conditions, such as the redundant hanger design for the Ted Williams Tunnel, as well as independent verification of the implemented repairs. When requested, the stem to stern team was also available to answer questions related to the details of each concern, identify the specific location of the reportable conditions, and review the progress or suggested remediation measures. The stem to stern safety review scope did not include quality assurance for the repairs.

March 2007 Implementation Meeting. An implementation meeting was conducted from March 26 through March 28, 2007, during Phase IA, to explain potential concerns, review the status of the open items, discuss possible remediation options/plans, and in some cases identify a person responsible for the implementation of the repair. Representatives from the stem to stern team, MTA, and CA/T attended the meeting, which helped to form the basis of the implementation plan. The "implementation plan" is a term used to describe the entire list of identified reportable conditions, the proposed plan of action to address the condition, and schedule when known. Throughout Phase II, the implementation plan was documented

in a spreadsheet maintained by the MTA. This spreadsheet also included status updates for the remediation measures and updates for the verifications performed by the stem to stern review, OIG, and/or FHWA.

Independent Verification. Throughout Phase II, the stem to stern team performed site visits and document reviews to verify that various reportable conditions have been addressed. The purpose of these reviews was not to serve as the quality control or quality assurance of the repair, but was instead to perform an independent verification that remediation measures have been implemented. Typically, the implementation verifications were performed after the repair had been performed. The verification efforts were often conducted in conjunction with, or with feedback from, representatives of the OIG, USACE, and FHWA.

For the structural reportable conditions, implementation verification commonly included a field visit to observe the remediation measure. The implementation verification field visits were performed in conjunction with the Phase II field work in October 2007 and March 2008. In addition, implementation verification site visits were also performed during June 2008. For life safety reportable conditions the verification often included review of available documentation, discussions with MTA and CA/T personnel, and an occasional field visit when required. Because many of the life safety reportable conditions directly relate to potential future maintenance issues, verification efforts also included a review of the preventive maintenance program to ensure that procedures are in place to address similar conditions in the future. Individual reports were created for each verification inspection or item resolution, and these reports discuss the steps taken to address the concern and the status of the reportable condition after the independent verification.

Summary of Phase I Implementation Status. Throughout the course of Phase II, implementation verifications were performed by the stem to stern team. At the time of this writing, all immediate concern (IC) conditions identified in Phase I had been closed or reclassified based on the verification inspections. These include such items as removal of loose concrete that presents an overhead hazard, removal of debris from the tunnel exhaust plenums, and repair of standpipe sections, as well as removal or replacement of loose, damaged, corroded, or improperly anchored signs and luminaires. Several of the R1 reportable conditions were closed or reclassified based on the verification inspections; however, several of the more significant R1 conditions remain open. These conditions include the installation of the sister hangers in the Ted Williams Tunnel to address ceiling anchors in questionable concrete, repair of the Sumner and Callahan tunnels to address ceiling anchors exhibiting slip or installed in deteriorated concrete, and the integration of the IPCS system. A summary of the implementation status, as of June 30, 2008, for the conditions identified in Phase I is shown in Table 3 below.

Table 3. Summary of Phase I Reportable Condition Implementation Status

Phase I Reportable Condition Classification	Total Identified	Open	Closed[1]	Reclassified[2]
IC: Immediate or dangerous condition	35	0	29	6
R1: Remediation recommended as soon as possible	80	27	52	1
R2: Remediation recommended in coordination with near-term maintenance and capital improvement programs	64	27	37	0

1. Items verified by stem to stern team and includes items reclassified to MI or MR because near-term safety concern was addressed as of June 30, 2008. Items reclassified to MR or MI will require future monitoring and/or maintenance because the conditions could worsen or reoccur in the future.
2. Items reclassified by stem to stern team based on work performed to address concern or re-inspection/re-evaluation of condition. Reclassified items would remain open in a lower classification, such as R1 or R2.

June 2008 Implementation Meeting. An implementation meeting was held on June 4, 2008, with representatives from the stem to stern team, EOT, MTA, CA/T, OIG, FHWA, and USACE. The purpose of the meeting was to discuss briefly the status of each Phase I reportable condition, particularly the open items. While the technical details were not discussed, the remediation plan for the open items was presented by the MTA. In many cases the item was assigned to a planned construction remediation contract to address several items at once, including deficiencies or punchlist items other than those reported by the stem to stern team.

CONCLUSIONS

Under the direction of safety review director Robert R. Rooney, WJE and its subconsultants, Schirmer Engineering and ESD, have completed Phase II of a stem to stern safety review of the Metropolitan Highway System. The MHS includes the Central Artery/Tunnel project; the Sumner, Callahan, and CANA Tunnels; as well as the Boston Extension and Prudential Tunnel. The investigation focused on the most safety critical elements of the structural and life safety systems. The conclusions summarized below are based on the investigations described in Phase IA and Phase II reports (Volumes IA-1 to IA-7 and II-2 through II-24).

Central Artery/Tunnel

Structural System

Proven structural systems, designed using appropriate modern standards, were used throughout the CA/T project. Typically, members were generously proportioned and thoughtfully detailed. Phase I of the safety review uncovered several conditions that were judged to be unsafe and warranted immediate remedial measures. These conditions include loose or unsound concrete over traffic, other loose construction materials, and fractured metal poles for traffic signals and luminaires. These conditions have been reported to and addressed by the appropriate responsible party.

Prior to the start of this review, deficiencies associated with the adhesive anchors supporting the suspended ceilings of the I-90 connector tunnels were well known. Retrofits of the I-90 mainline roadways and connector ramps have been completed. In spite of extensive studies of the structural and fire resistance of the adhesive anchors in the Ted Williams Tunnel, questions remain as to their long-term safety. Retrofits of anchors installed in suspect concrete have not yet been completed, and pullout and creep testing of the anchors is needed to confirm that they will perform for several decades. Also, retrofit of the ceiling support system is recommended to prevent progressive collapse in the event of a severe fire.

The Phase I review identified several conditions of concern with respect to the structural capacity of main members that required further investigation in Phase II. With one exception (cracking of Leverett pier), the Phase II studies indicated adequate structural capacity. In the case of Leverett Pier, installation of grouted transverse reinforcement in the pier cap is recommended to provide a level of shear and torsion strength consistent with that required by the original design criteria. In the meantime, restrictions on permit loads should remain in place, and lane closures that shift traffic to the shoulders should not be allowed. Also, electronic crack width monitoring should continue while detailed repair plans are developed for installation as soon as possible.

The Phase II study also identified a number of threats to long-term performance and structural safety:

- Tunnel and building leaks that promote corrosion of embedded reinforcement and threaten sensitive electrical equipment
- Possible voids in post-tensioning tendons
- Pattern cracking of tunnel roof structures and pier columns
- Premature deterioration of rigid overlays

Strategies for managing these threats have been recommended.

Life Safety Systems

The design of life safety systems was generally consistent with CA/T design criteria and the governing standard for tunnels, NFPA 502. The systems were found to be conservative, with features that protect the public, workers, and emergency responders in a majority of incident scenarios. The systems utilize robust and redundant hardware components that are powered by equally robust and redundant power systems.

Nonetheless, many significant life safety system deficiencies and concerns exist. The most important concerns relate to the full implementation of planned safety features including automatic fire detection and the integrated project control system.

Sumner and Callahan Tunnels

Structural System

As identified in Phase I, the primary concern remains the long-term performance of the adhesive anchors supporting the suspended exhaust plenum ceilings in both the Sumner and Callahan tunnels. At the Sumner Tunnel, the anchors exhibit good performance despite having been installed in spalled and delaminated concrete, yet some of the Sumner Tunnel anchors failed recent proof tests. On the other hand, the Callahan Tunnel anchors exhibit slip but performed well in recent proof tests. At both tunnels, complete replacement of the adhesive anchors with mechanical anchors is recommended to assure long-term reliability. In conjunction with the anchor replacement at the Sumner Tunnel, the damaged concrete liner should be repaired. The MTA has engaged consultants to develop details of repairs to both tunnels.

Life Safety Systems

The most significant finding relates to the emergency ventilation system and emergency egress features. To assure that sole reliance for life safety in these tunnels is not dependent on a single system, it is recommended that installation of a fire suppression system be considered. In addition, other near-term repairs and upgrades to various life safety systems have been recommended.

CANA Tunnel

Only minor concerns with the respect to the structural and life safety systems of the CANA tunnel were identified.

Boston Extension and Prudential Tunnel

Structural System

The structural systems employed in the buildings and bridges spanning the Boston Extension are straightforward, but not as robust as the CA/T structures. The structures along the Boston Extension are performing as expected given over four decades of service in a harsh northern climate. Chloride-induced corrosion of embedded reinforcement poses both short-term safety hazards in the form of loose concrete over traffic and structural capacity concerns where severe delaminations have compromised the strength of pier cap cantilevers. Similarly, some steel members have suffered significant section loss due to corrosion where moisture and salts have accumulated.

Also, there are concerns with structures over the Boston Extension that are owned by third parties. In particular, the precast double tee system supporting the first level of a building exhibits signs of severe

deterioration and distress. Also, corrosion damage has also compromised the connections supporting the suspended ceiling in a portion of the Prudential Tunnel.

Life Safety Systems

Although the Prudential Tunnel was built incrementally over a twenty-year period, life safety systems are reasonably thorough. However, not all of the elements required by NFPA 502 are present, and those that were provided are not fully compliant with the standard.

Closing Remarks

In closing, the stem to stern review has uncovered numerous safety deficiencies in both the structural and life safety systems. Conditions posing immediate safety threats have been addressed, and plans are in place to implement recommendations to remediate other near-term concerns.

In addition, there are long-term threats to structural integrity and performance of life safety systems. Decades of exposure to the harsh northern climate have taken their toll on structures along the Boston Extension, as well as the Sumner and Callahan tunnels. Although more conservatively designed, the structures of the CA/T are also threatened by brackish water leaking through tunnel joints and deicing salts on roadways. Given the importance of this vital transportation facility, the focus should be on rigorous inspections and maintenance of protection systems and other elements with limited service life, such that the primary structural systems last indefinitely.

Lastly, the life safety protection for tunnels is continuing to evolve and mature; upgrades are inevitable as new systems are developed to detect and mitigate potential life safety threats.

In a closing letter from Stem to Stern Director Robert Rooney to Massachusetts Turnpike Chairman and Transportation Secretary Bernard Cohen lists five recommendations in response to the findings of the stem to stern safety review:

1. Continue oversight through the Secretary of Transportation on an ongoing basis until the reported conditions are resolved.
2. Conduct a peer review for the design and installation of repairs for specific complex issues.
3. Establish detailed criteria and conduct an aggressive inspection timetable for structures experiencing deferred maintenance.
4. Develop a funding plan, to include the CA/T Repair and Maintenance Trust Fund, to provide the necessary resources to properly maintain the MHS.
5. Formalize agreements between the MTA and third party owners to allow for expedited mitigation of immediate safety concerns on structures.

These recommendations provide a framework for implementation of the recommendations arising from the stem to stern safety review of the MHS. The recommendations address both near-term repairs and long-term maintenance of the structural and life safety systems.